

Calibration Methods for the LISA Pathfinder Drag-Free System and Expected Performance

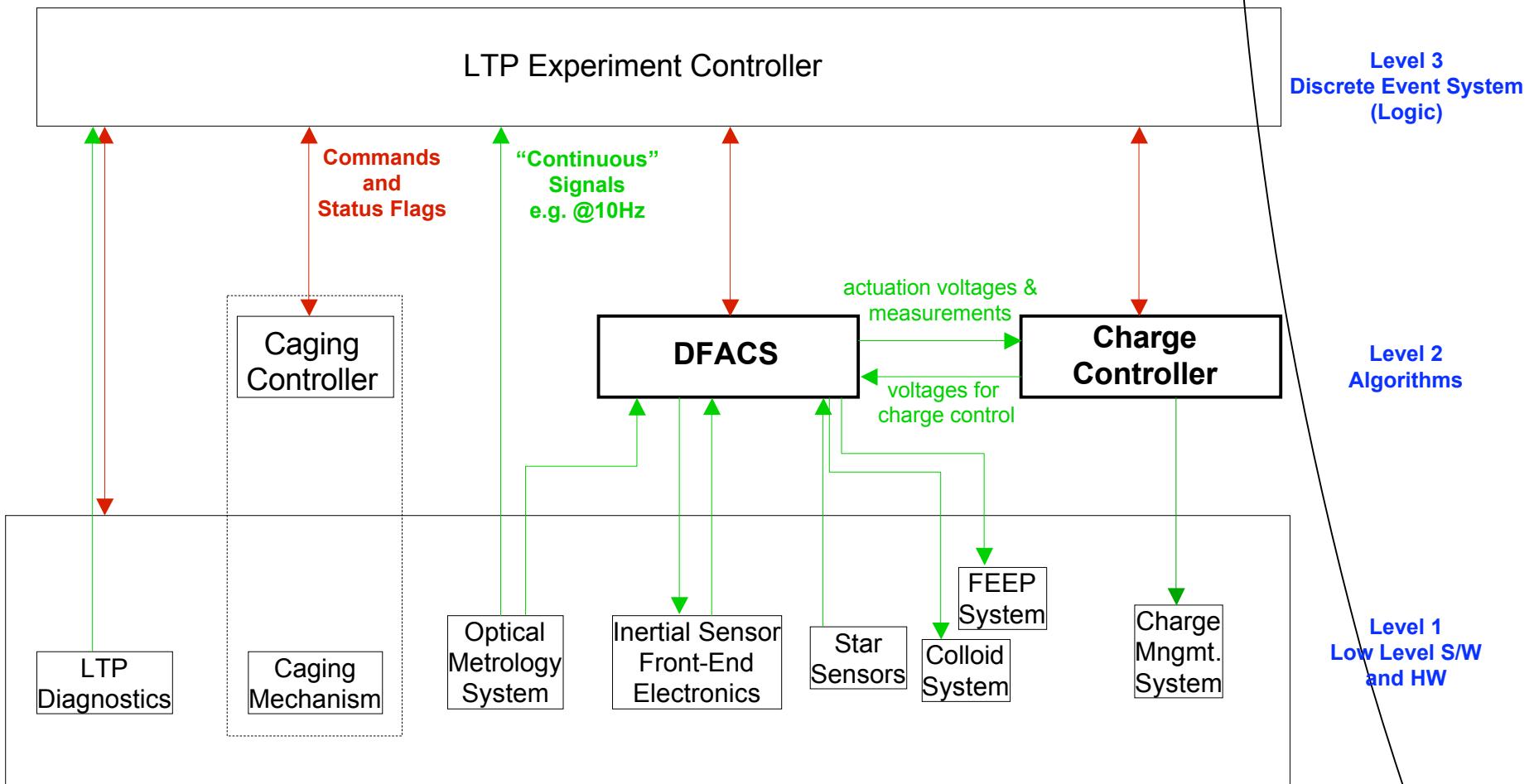
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Walter Fichter, Tobias Ziegler,
EADS Astrium GmbH

Stefano Vitale
University of Trento

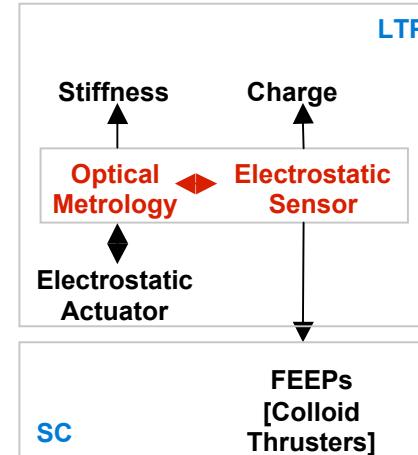
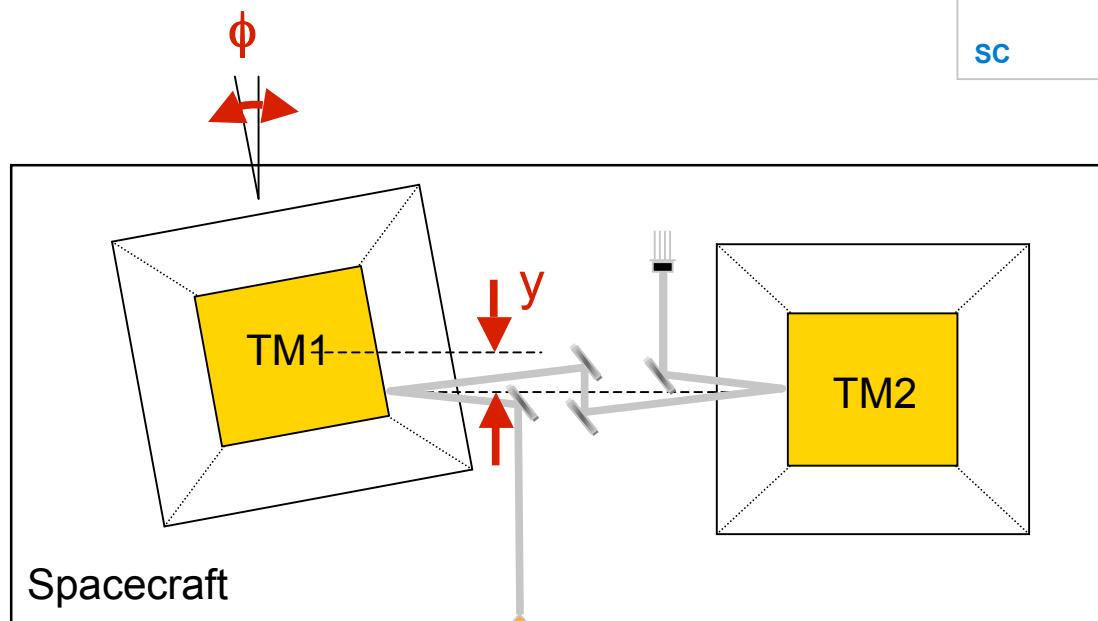


LTP Experiment, DFACS, and Charge Control



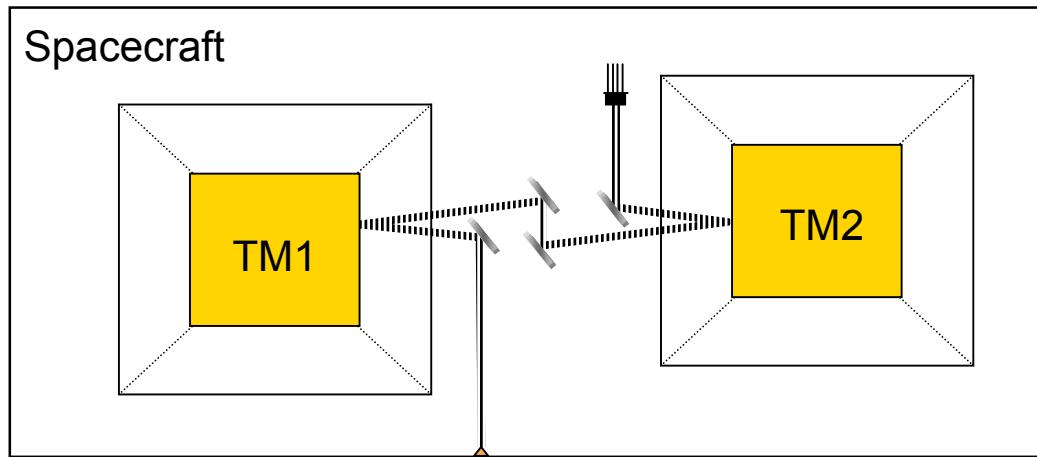
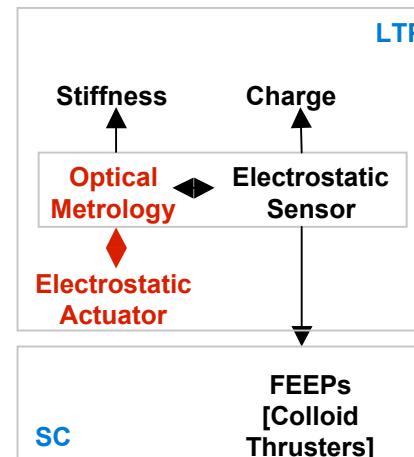
Sensor Cross Calibration

- ◆ compare angular outputs $\diamond \phi$
- ◆ slew TMs & compare x-outputs $\diamond y$



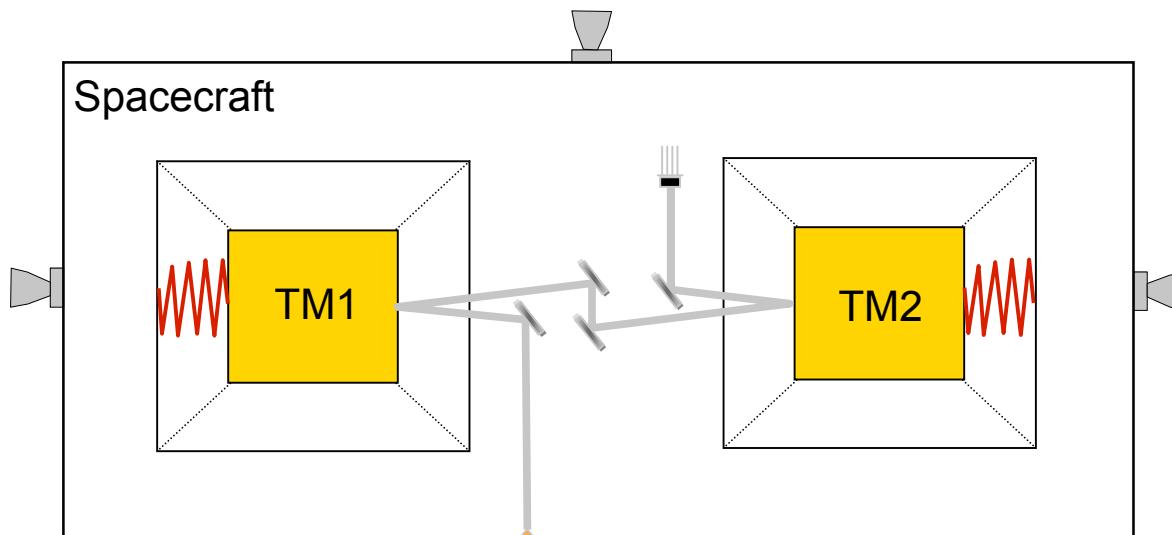
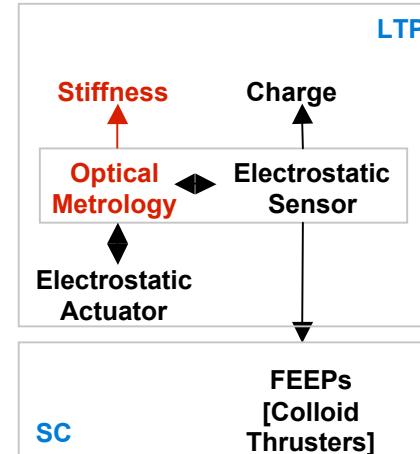
Electrostatic Actuation Calibration

- ◆ calibrate effect of cross-axes actuation ◇ sensitive axis
- ◆ actuate test mass cross-axes
- ◆ measure x-output



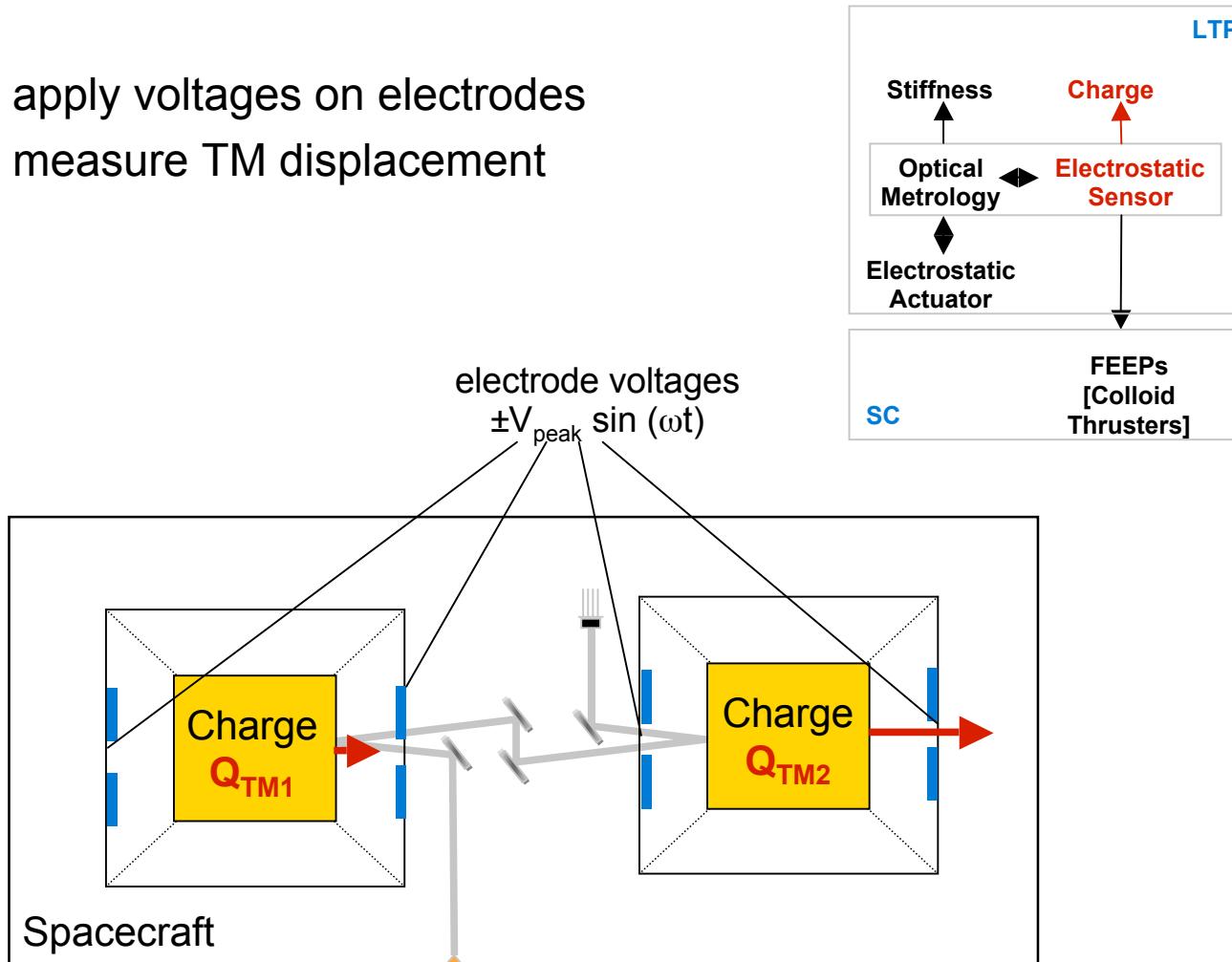
Stiffness Calibration Measurement

- ◆ excite TM2 electrostatic suspension
- ◆ excite TM1 with thrusters
- ◆ measure differential displacement



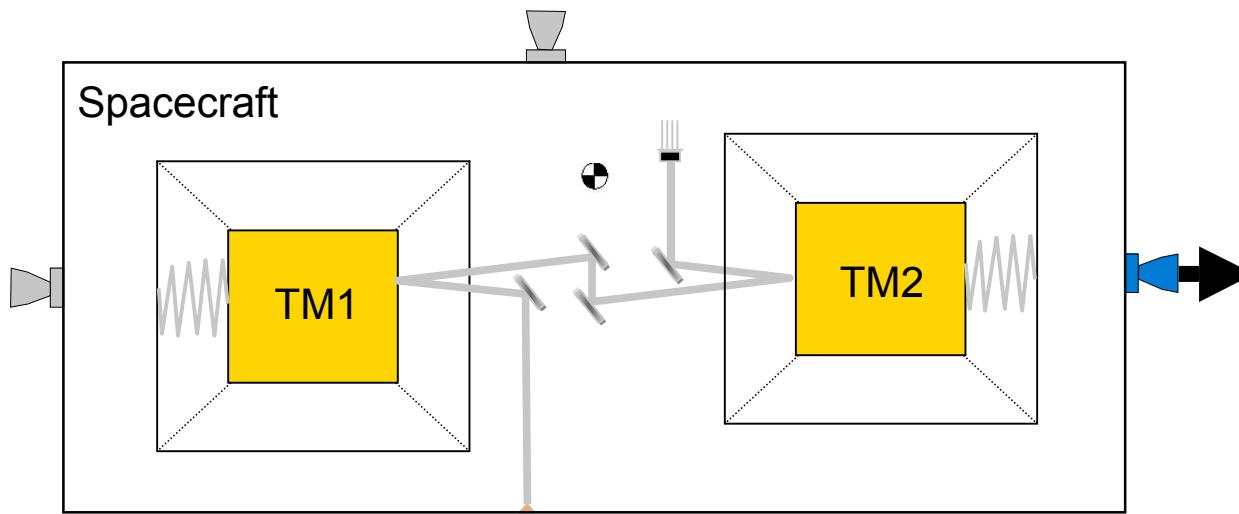
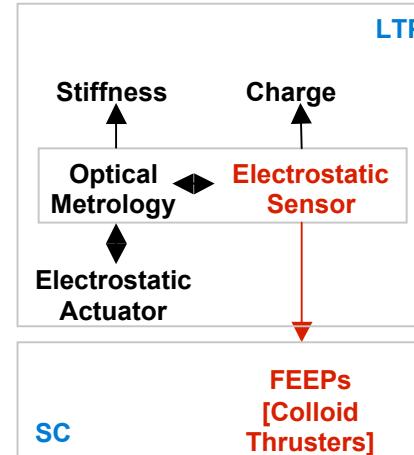
Test Mass Charge Measurement

- ◆ apply voltages on electrodes
- ◆ measure TM displacement



Thruster Calibration

- ◆ add test signal on each thruster
- ◆ measure TM (drag-free) coordinates



Calibration Task Summary

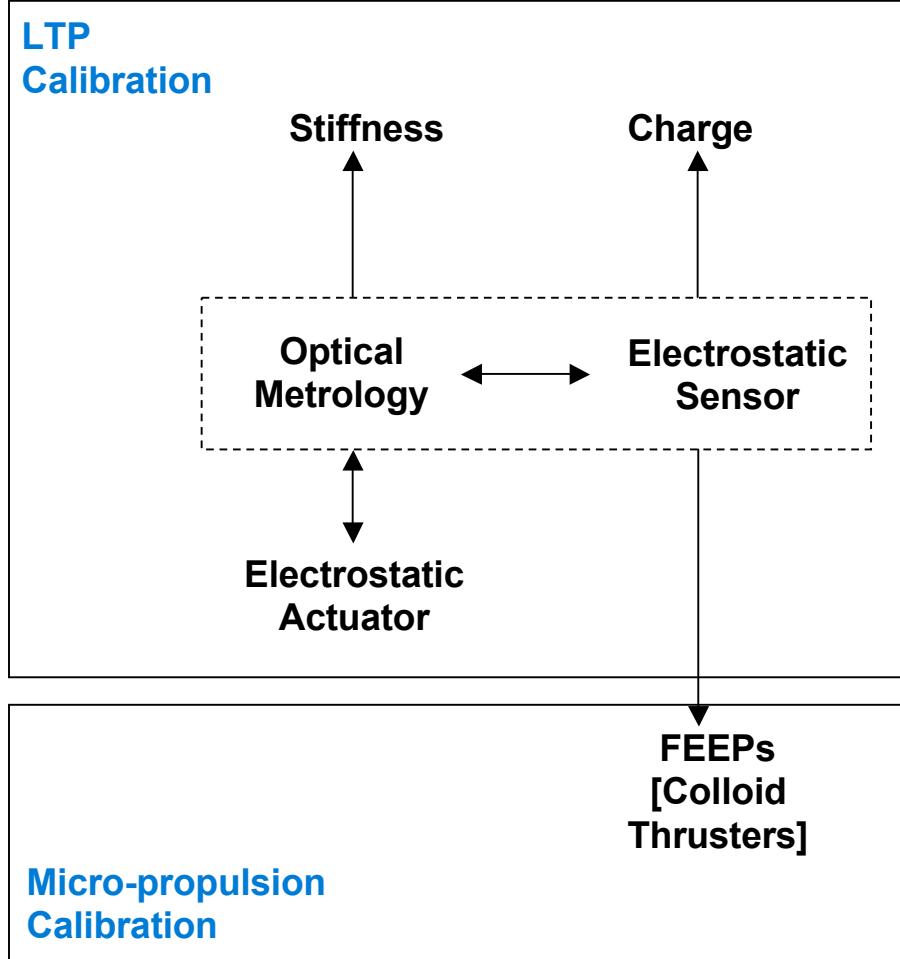


Test Mass
Parameters

Test Mass
Sensors

Test Mass
Actuator

Spacecraft
Actuator



Calibration Task Summary

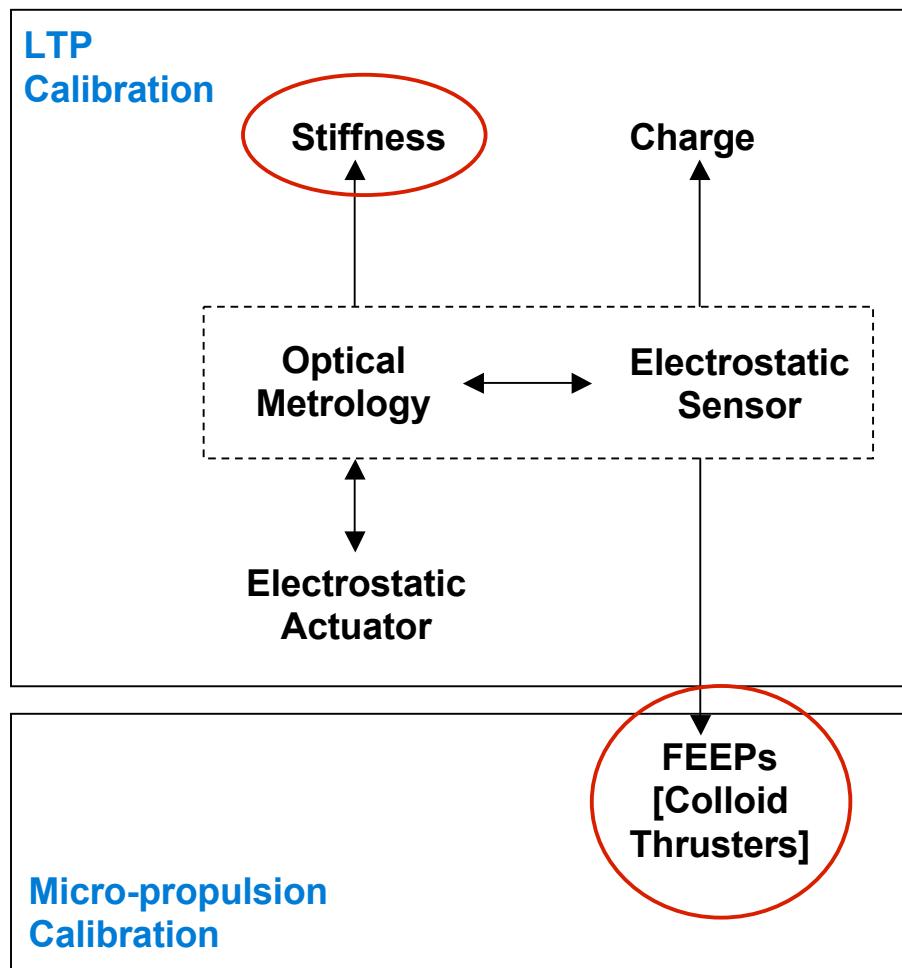


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Parameters

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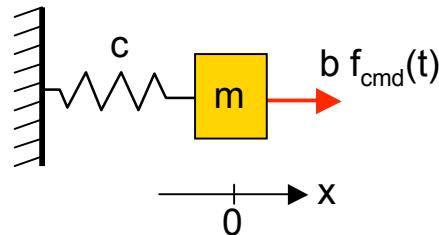
Test Mass
Actuator

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Actuator



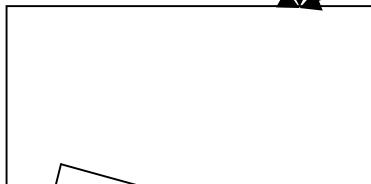
Calibration Simple Example

$$\ddot{x}(t) + \frac{c}{m} \cdot x(t) = \frac{b}{m} \cdot f_{cmd}(t)$$



$$x(k+2) + x(k) = a_1 \cdot x(k+1) + b_1 \cdot f_{cmd}(k+1) + b_0 \cdot f_{cmd}(k)$$

discrete time description



one sample

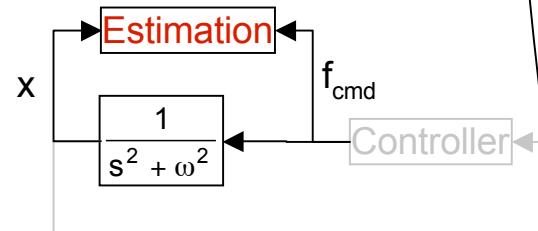
all samples, least squares solution



recovery of physical parameters

Properties of Calibration Algorithm

- ◆ considers plant dynamics
 - ◊ controller knowledge NOT required
- ◆ transients possible
 - ◊ steady state NOT required
- ◆ discrete-time parameter estimation, but continuous-time (physical) parameter recovery
- ◆ can be solved recursively (on-board capability)
- ◆ recursive algorithm formally identical to optimal filtering



Method	θ	Ψ	γ
optimal filter parameter identification	states parameters	system parameters signals (cmd, meas)	meas meas

$$\gamma = \Psi\theta$$

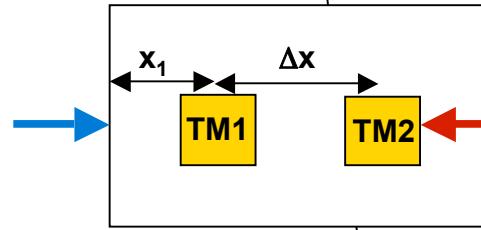
Stiffness Calibration Experiment

◆ Dynamics

$$\Delta \ddot{x}_2 - \omega_{2xx}^2 \Delta x = [g_{sus,x_2} (\omega_{2xx}^2 - \omega_{1xx}^2)] \left(f_{sus,x_2} / m \right)$$

test signal
move test mass

test signal
move spacecraft



◆ Test signals

- Frequencies near expected stiffness eigen-frequencies
- Amplitudes such that actuation limits and max. test mass displacements are within allowed limits

x_1 : Amplitude: $2 \cdot 10^{-6}$ m,

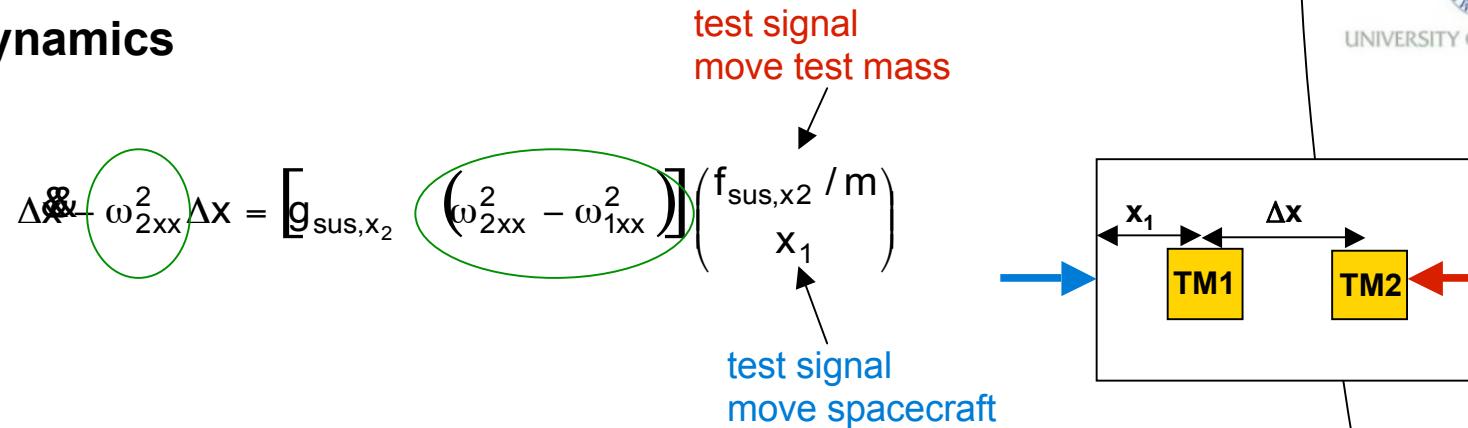
$f_{sus,x_2}/m$: Amplitude: $1 \cdot 10^{-9}$ m/s²,

Frequency: 10 mHz

Frequency: 1 mHz

Stiffness Calibration Experiment

◆ Dynamics



◆ Test signals

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- Amplitudes such that actuation limits and max. test mass displacements are within allowed limits

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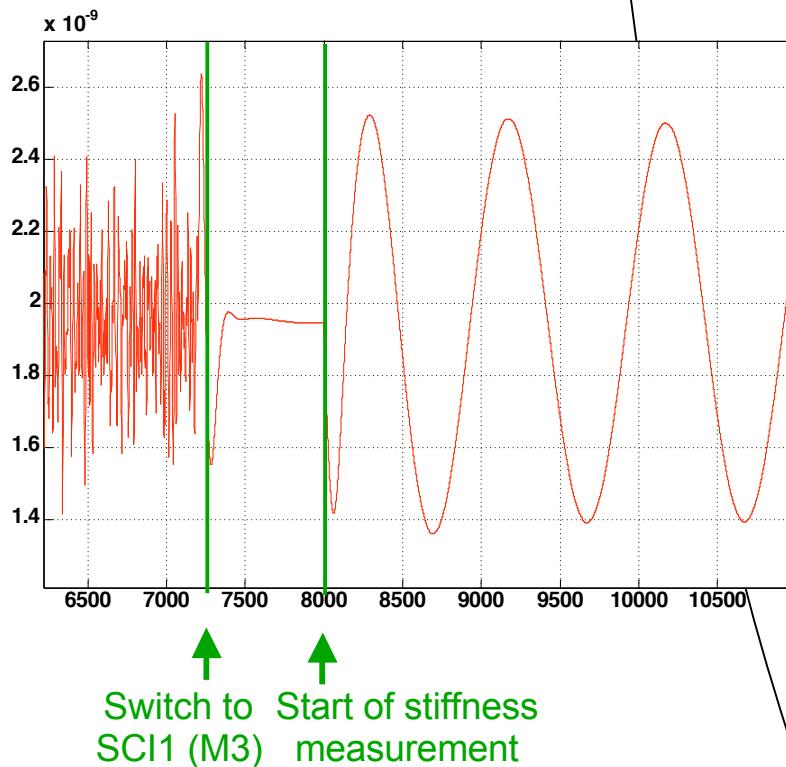
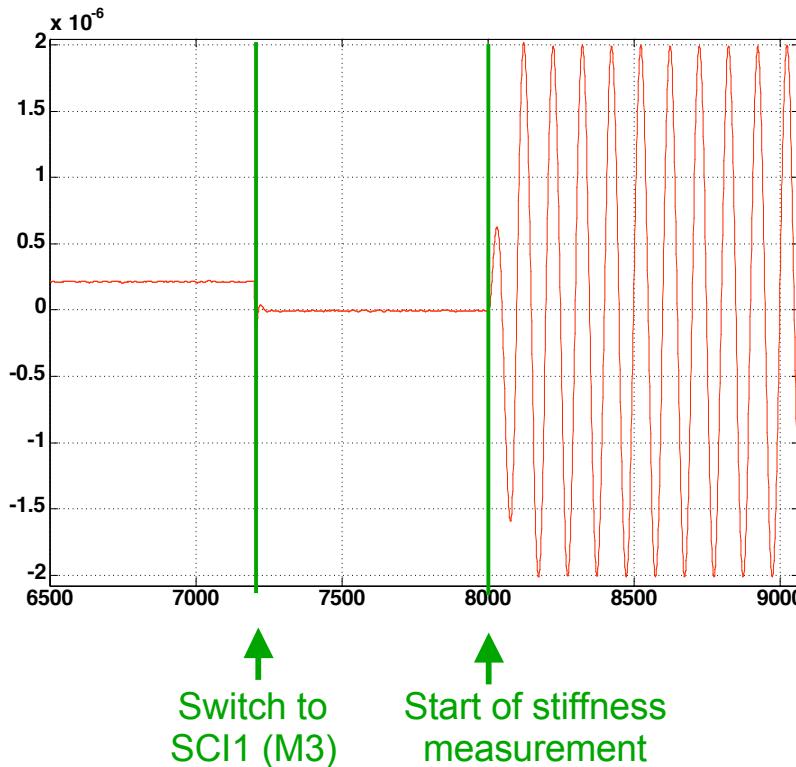
Frequency: 10 mHz

Frequency: 1 mHz

Stiffness Calibration Time Histories

◆ Test (excitation) signals

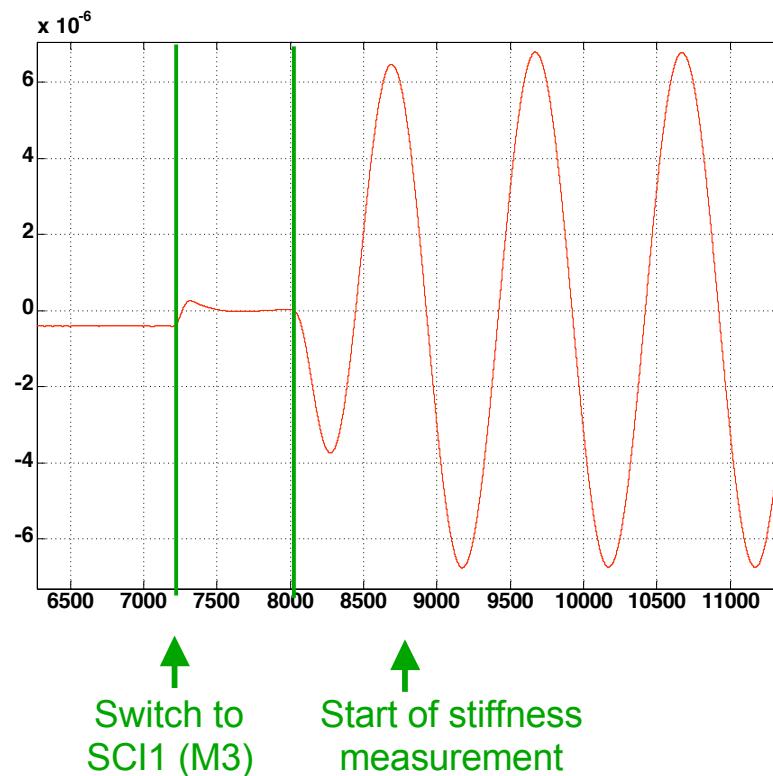
- TM1 x-axis displacement (x_1 , drag-free controlled)
- Total suspension force command (f_{sus,x_2})





Stiffness Calibration Time Histories

- ◆ Measurement signal $\Delta x = x_2 - x_1$





Stiffness Calibration Results

◆ Performance results

```

Results of Bootstrap Iteration (1. Step: LS-Method, Further Steps: IV-Method)
-----
Integration Time :02000.0 s
Name of Experiment :lisasymp06_stiffness_3.mat
-----
|      | omegasquare_xx_2 | omegasquare_xx_diff | omegasquare_xx_1 | sus_tf_gain (x2)
|-----|
| 1. Step (LS) | -5.6339e-007 | -7.0745e-007 | +1.4406e-007 | -0.0000
|   Error     | 074.83 [%]    | 001.06 [%]    | 109.46 [%]    | 003.73 [%]
|-----|
| 2. Step (IV) | -2.2470e-006 | -6.8710e-007 | -1.5599e-006 | +0.9990
|   Error     | 00.38 [%]    | 03.90 [%]    | 02.40 [%]    | 0.10 [%]
|-----|
| 3. Step (IV) | -2.2436e-006 | -6.8717e-007 | -1.5564e-006 | +0.9990
|   Error     | 00.23 [%]    | 03.89 [%]    | 02.17 [%]    | 0.10 [%]
|-----|

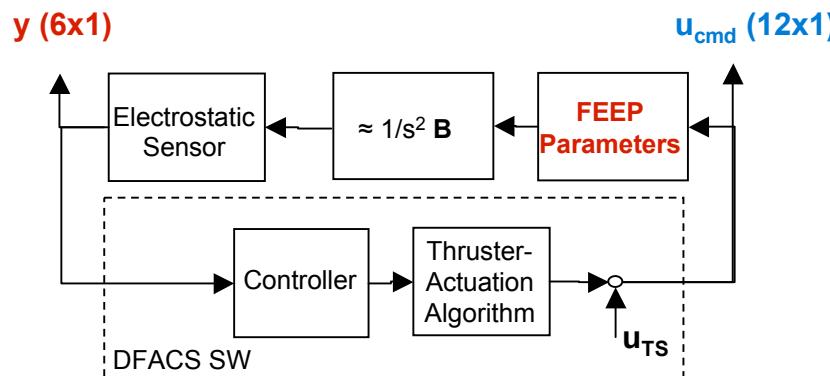
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◆ Results with

- **Integration time >2000 sec typical**
- **Interferometer readout used**
- **Test mass “direct” disturbance acceleration driving**

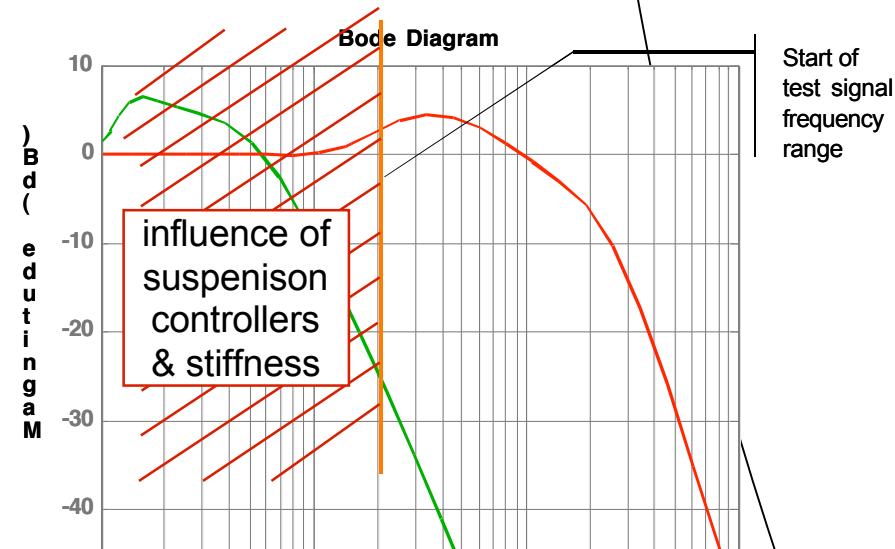
◆ Here: need of “Instrumental Variables” method

Micro-Propulsion System Calibration: Experiment Layout



- ◆ **12 sinusoidal test signals**
 - as direct thrust commands
 - amplitudes of $8 \mu\text{N}$
- ◆ **Separated in frequency**
 - frequency range: 20-31 mHz
- ◆ **Permanently biased**
 - ensure positive thrust
 - cover different thrust levels

- ◆ **Control Mode: SCI1 (M3)**
- ◆ **Recording of**
 - 6 drag-free coordinates y
 - 12 thrust commands u_{cmd}





Micro-Propulsion System Calibration: Results

◆ Performance results after 10 000 s integration time:

- Total number of estimated parameters: $(1 + 2 + 3) \underbrace{+}_{k} \underbrace{-}_{u} \underbrace{-}_{d} 12 = 72$

Parameter	Worst case	Average
k error in %	1.3	0.8
u error in deg	1.3	0.6
d error in %	4.6	2.0

not so important;
can be improved with better
actuation cross-talk knowledge

◆ Performance depends on

- Delay (FEEP + OBC + IS)**
 - a-priori knowledge <100 msec sufficient
 - can also be estimated
- Spacecraft mass & geometrical properties**
 - known a-priori with sufficient accuracy
- Cross-talk of electrostatic actuation**
 - current specification values used

not a serious driver

uncertainties must kept small
drives performance

Conclusion

- ◆ **Calibration algorithms developed and first tests performed (with nonlinear E2E simulation)**
 - for calibrations / preliminary measurements prior to science measurements
- ◆ **Same “core” algorithm used for all problems**
 - can be parameterized as parameter identification or optimal (Kalman) filter
 - has on-board capability
- ◆ **Results look good**
 - typically about 2% or less
 - sometimes need of “Instrumental Variables” method to achieve required accuracy